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Region-based shielding of visual search from salient distractors:

Target detection is impaired with same- but not different-dimension distractors

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Abstract

Shielding visual search against interference from salient distractors becomes more efficient over time for display regions where distractors appear more frequently, rather than only rarely (Goschy et al., 2014). We hypothesized that the locus of this learnt distractor probability-cueing effect depends on the dimensional relationship of the to-be-inhibited distractor relative to the to-be-attended target. If they are defined in different visual dimensions (e.g., color-defined distractor and orientation-defined target, as in Goschy et al., 2014), distractors may be efficiently suppressed by down-weighting feature contrast signals in the distractor-defining dimension (Zehetleitner et al., 2012), with stronger down-weighting applied to the frequent vs. the rare distractor region. However, given dimensionally coupled feature contrast signal weighting (cf. Müller et al., 1995), this dimension-(down-)weighting strategy would not be effective when the target and the distractors are defined within the same dimension. In this case, suppression may operate differently: by inhibiting the entire frequent distractor region on the search-guiding master saliency map. The downside of inhibition at this level is that, while it reduces distractor interference in the inhibited (frequent distractor) region, it also impairs target processing in that region – even when no distractor is actually present in the display. This predicted *qualitative* difference between same- and different-dimension distractors was confirmed in the present study (with 184 participants) – thus, furthering our understanding of the functional architecture of search guidance, especially regarding the mechanisms involved in shielding search from the interference of distractors that consistently occur in certain display regions.

Keywords: visual search, perceptual learning, attentional capture, location probability cueing, location suppression, dimension weighting

When looking for a unique target object within a rich visual scene, there are often other objects that stand out from the background of non-target items and that may capture attention before the target is attended. In such visual *pop-out* search tasks, observers become more efficient, over time, in minimizing the interference generated by such salient but task-irrelevant distractors when these are consistently occurring in certain regions of the search display (Goschy, Bakos, Müller, & Zehetleitner, 2014). However, the mechanisms underlying this learning effect, termed *probability cueing of distractor locations* (Goschy et al., 2014), are poorly understood: Do observers learn to suppress distractors based on their likely location alone? Or does space-based suppression combine with feature- or dimension-based suppression mechanisms in some circumstances? And, when there are no effective means of object-based suppression, does space-based suppression become so strong that it affects processing of the search target (counter the intention) as well as of the distractor? These questions were addressed in the present study. – Before developing these questions and considering in detail how probability cueing of distractor locations may work, we review some key notions concerning the functional architecture underlying the competition of unique, *singleton* target and distractor objects in otherwise homogeneous search arrays.

Modulation of interference in involuntary attentional capture

Attentional capture by task-irrelevant objects is usually investigated using variants of the *additional-singleton paradigm* (Theeuwes, 1992; see Yantis, 1996, 2000, for a discussion). While the search display consists of one (task-relevant) singleton-feature target amongst homogeneous non-targets, some or all displays include an additional (task-irrelevant) singleton-feature distractor. Typically, the additional singleton is more salient than the target – frequently, as in Theeuwes (1992), the target is defined by a unique shape (e.g., a diamond among circles) and the distractor by a unique color (e.g., a red circle among green

shapes) – so that, generally, it is highly likely to capture the observer's attention before the target is selected, thereby prolonging reaction times. Such attentional shifts are considered involuntary because they interfere with the task of producing a speeded response to the target.

This interference of salient additional-singleton distractors can be reduced in some situations (e.g., Gaspelin, Leonhard, & Luck, 2015, 2017; Leber & Egeth, 2006a, 2006b; Müller, Geyer, Zehetleitner, & Krummenacher, 2009). Additionally, Zehetleitner, Goschy, and Müller (2012) showed that the interference reduction does not critically depend on the *search mode* (cf. Bacon & Egeth, 1994) adopted by observers (whether *feature* or *singleton search mode*), but on distractor practice (see also Vatterott & Vecera, 2012, and Gaspelin & Luck, 2017, for the role of practice for reducing distractor interference). This indicates that observers can acquire some efficient strategy to suppress color-defined distractors when searching for a shape- (or orientation-) defined target. But exactly how this exclusion of distractors is implemented in the functional architecture of search guidance remains unclear.

One clue to answering this question is provided by Liesefeld, Liesefeld, Töllner, and Müller (2017). Instead of using a color-defined distractor, both distractor and target were defined by orientation: the (less salient) target was defined by a 12° tilt from the vertical, and the (more salient) distractor by a 45° tilt in the opposite direction to the target. Using these stimuli, Liesefeld et al. (2017) observed massive and persistent distractor interference (of 225 ms) over a lengthy EEG experiment. There was no evidence that observers could reduce the attentional capture by the singleton distractor. Rather, the distractors attracted spatial attention – as evidenced by a distractor N2pc wave, a negative EEG deflection at posterior electrodes contralateral to the distractor. Generally, the N2pc is taken to reflect the allocation of attention to an object in the search display (e.g., Luck & Hillyard, 1994; Eimer, 1996; Woodman & Luck, 1999, 2003; Töllner, Rangelov, & Müller, 2012). Crucially, the distractor N2pc was elicited prior to a shift of attention to the target, as evidenced by a delayed target

N2pc. Such a signature pattern of successive distractor- and target-related N2pc waves had never been consistently demonstrated before. A reason for this might be that previous studies focusing on the N2pc typically used shape-defined targets and color-defined distractors, making it easy to selectively up-weight target and/or down-weight distractor signals (Hickey, McDonald, & Theeuwes, 2006; Kiss, Grubert, Petersen, & Eimer, 2012; Jannati, Gaspar, & McDonald, 2013; Burra & Kerzel, 2013; Wykowska & Schubö, 2011; among the exceptions are studies with both target and distractor defined in the color dimension, which will be considered further in the General Discussion).

The role of dimension weighting in involuntary attentional capture.

Thus, it would appear that when searching for an orientation- (or shape-) defined target, the interference caused by a salient singleton distractor can be effectively reduced when the distractor is color-defined (i.e., when it is a *different-dimension* distractor), but not when it is also orientation- (or shape-) defined (i.e., when it is a *same-dimension* distractor). In fact, this pattern is predicted by the *dimension-weighting account (DWA)* developed by Müller and colleagues (e.g., Found & Müller, 1996; Müller, Heller, & Ziegler, 1995; Müller, Reimann, & Krummenacher, 2003; Krummenacher, Müller, Zehetleiter, & Geyer, 2009). In essence, DWA is a variation of the *Guided Search* model (e.g., Wolfe, 1994; Wolfe, 2007), which assumes that the allocation of focal attention to items in visual search is based on a pre-attentively computed spatial priority map (henceforth referred to as *master saliency map*): items achieving the highest overall-saliency are attended with priority. The saliency that items take on on this map depends on their feature contrast to other items in their local surround, within all pertinent feature dimensions (e.g., color and orientation contrast). Additionally, this contrast can be top-down enhanced for features that define the searched-for target and possibly also reduced for task-irrelevant features – where the down-weighting of

specific features would correspond to *first-order feature suppression* in the terminology recently introduced by Gaspelin and Luck (2017). The feature contrast signals thus computed are then integrated across dimensions on the master saliency map and subsequently drive spatial selection. At the heart of DWA is the notion that this integration operates in a dimensionally weighted fashion (in contrast to simple saliency summation models which assume non-weighted integration and to models assuming only feature-specific weighting). *All* signals from specific dimensions may be assigned a greater or a lesser influence on guiding the allocation of attention than *all* signals from other dimensions – where the down-weighting of a whole feature dimension would correspond to *second-order feature suppression* in Gaspelin and Luck's (2017) terminology (i.e., suppression of items on the basis of differences, or discontinuities, within a given dimension, irrespective of the actual feature values). Accordingly, on the DWA, non-spatial visual selection is primarily dimension-based, rather than feature-based, without denying an element of feature-based selection (see General Discussion for further details).

Role of dimension weighting in the probability cueing of distractor locations

The present study was designed to examine whether the functional architecture envisaged by DWA (see above) would also help us understand how the probability cueing of distractor locations is mediated. Besides processes of location-independent attentional selection as discussed above, search performance is greatly influenced by the spatial distribution of targets and distractors in the search array. It is well-established that observers can learn to exploit uneven distributions of target locations in order to facilitate search: targets are detected faster at locations where they appear more frequently (e.g., Anderson & Druker, 2010; Fecteau, Korjoukov, & Roelfsema, 2009; Geng & Behrmann, 2002; 2005), which Geng and Behrmann (2002) termed a *target location probability cueing effect*.

Similarly, observers can learn to exploit the statistical distribution of task-irrelevant distractors to improve performance: over time, they become better at suppressing locations where distractors appear frequently (e.g., Kelley & Yantis, 2009; Leber, Gwinn, Hong, & O'Toole, 2016; Reder, Weber, Shang, & Vanyukov, 2003). Note, though, that the relevant demonstrations were limited to sparse visual displays that contained only a few target and distractor stimuli with a very limited number of possible distractor locations.¹ Goschy et al. (2014) showed that distractor location probability learning does generalize from single, specific locations to entire regions of dense search displays. They presented a slightly tilted gray target bar (i.e., an orientation-singleton) among 36 vertical gray non-target bars. In half of the search arrays, one of the vertical non-targets was red, serving as a highly salient color-defined (i.e., different-dimension) distractor. When present, distractors appeared with 90% probability in one half of the display (frequent distractor region) and with 10% in the other half (rare distractor region). Goschy et al. (2014) found that the distractor captured less attention when it occurred in the frequent as compared to the rare region. This result suggests that (at least with different-dimension distractors) we can exploit uneven spatial distractor distributions to facilitate search performance. However, it remains unclear exactly how this suppression is implemented, and whether it works in the same way with same- as with different-dimension distractors.

¹ Reder et al. (2003) used a variation of the *negative-priming* paradigm (adapted from Tipper, Brehaut, & Driver, 1990): displays consisted of 1 target and 1 distractor, with 4 possible locations, one of which was most likely to contain a distractor. In Kelley and Yantis (2009), the task-relevant red-green dot pattern consistently appeared in the display center, and a distractor (composed of the same colors) could appear at one of two, equally likely peripheral locations. Leber et al. (2016) used a variation of the *contingent-capture* paradigm (e.g., Folk, Remington, & Johnston, 1992): there were 4 display locations/items (arranged in the form of a square), with the distractor display preceding the target display; distractors (which were singled out from the background stimuli by the same feature as the target: the color red) were most likely to appear at one location, defined by a fixed relationship with the likely target location that was indicated by a central arrow at the start of a trial.

Rationale of the present study

In principle, there are three possibilities of how spatial shielding from distractor interference may work: spatially selective suppression at (i) the global, master saliency level, (ii) the specific feature level, or (iii) the dimensional level (see Figure 1 for an illustration).

Global-saliency-based suppression. One possibility (depicted in Figure 1A) is that the reduced interference from distractors in the frequent distractor region is due to a global bias against the allocation of spatial attention to this region. In terms of search architecture, this would be implemented at the level of the search-guiding master saliency map of the search array (in Gaspelin & Luck's, 2017 terminology, this corresponds to *global-saliency suppression*). Suppression at this level entails that if the frequent distractor region was inhibited on the master saliency map, the processing of search targets appearing in this spatially suppressed region should be impaired, too. This impairment should even be evident on trials on which no distractor is present, because learned, persistent global suppression of the frequent distractor region would operate on all trials, whether or not a distractor appears. Additionally, it would be independent of whether the distractor is defined in the same or a different dimension to the target.

Feature-based suppression. Alternatively (as depicted in Figure 1B), spatial shielding may operate at a level below the search-guiding master saliency map, where features and feature contrast signals are computed, which are then integrated into the master saliency map. Distractor suppression could operate on the feature map, down-modulating the distractor-defining feature directly (in Goschy et al., 2014: the feature 'red'), with stronger down-modulation applied to the frequent as compared to the rare region. This is essentially a spatially selective version of first-order feature suppression (cf. Luck & Gaspelin, 2017). Suppressing distractor feature signals in the frequent distractor region (more than in the rare region) would attenuate their weight when transferred to the corresponding locations on the

master saliency map, making them less competitive for the allocation of focal attention. If such a direct feature weighting is the general mechanism by which shielding works, it would predict *no* impairment of processing for targets in the frequent versus the rare distractor region, whether the distractor is defined in the same or a different dimension to the target (as in both cases, only the distractor feature is suppressed).

Dimension-based suppression. Alternatively, as assumed by the DWA (and depicted in Figure 1C), spatial shielding could operate on the dimension-specific feature-contrast map, down-modulating the strength of any feature-contrast signals in the dimension in which the distractor is singled out from the non-targets (in Goschy et al.: the dimension ‘color’), more so for the frequent as compared to the rare region. This is essentially a spatially selective version of second-order feature suppression (cf. Gaspelin & Luck, 2017). Accordingly, a dissociation would be expected between conditions with distractors defined in the same versus a different dimension to the target (cf. Müller et al., 2009; Zehetleitner et al., 2012): Impairment of target processing in the frequent as compared to the rare distractor region would *not* be expected when the distractor is defined in a different dimension to the target, in which case any signals from the distractor dimension can be suppressed without impacting signals from the target dimension. But impairment would be expected if the distractor is defined within the same dimension as the target: in this case, because of dimensional coupling, applying dimension-based suppression would impact target as well as distractor signals.²

² An alternative strategy to dimension-based suppression (which might be deemed counter-productive, as the target can be detected only on the basis of signals in the single critical dimension) might be to resort to inhibition at the level of the master saliency map. But this would again lower the response of saliency units to the target (as well as the distractor) in the frequent (suppressed) region – in line with global spatial shielding (see above). Accordingly, with same-dimension distractors, a target location effect (slowed responding to targets within the frequent vs. the rare distractor region) would be expected in both cases.

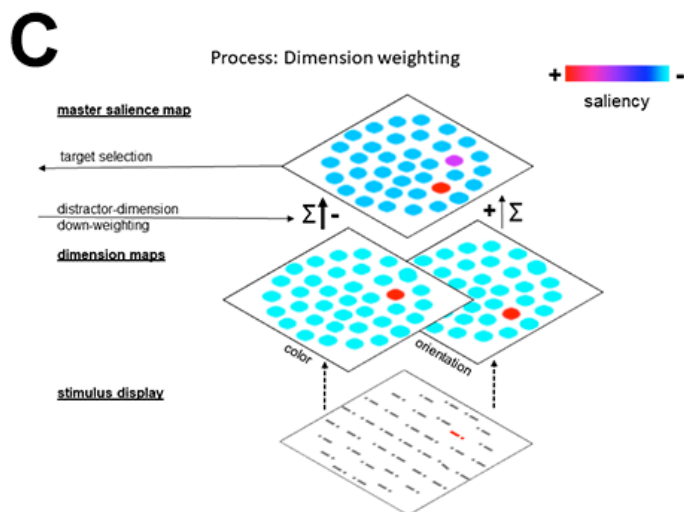
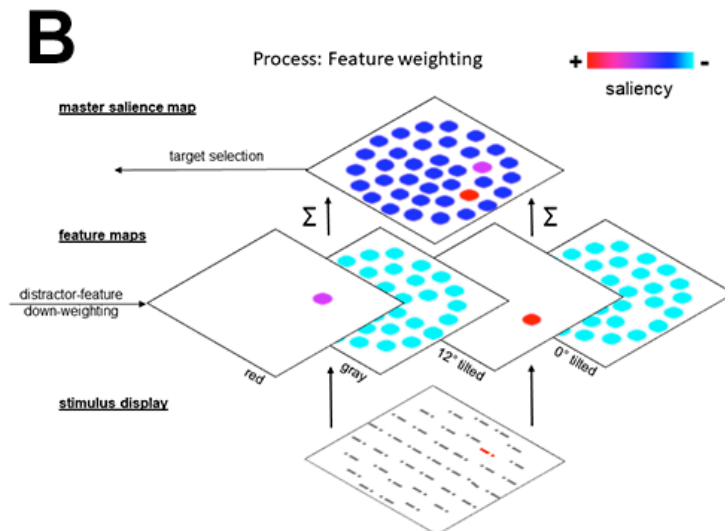
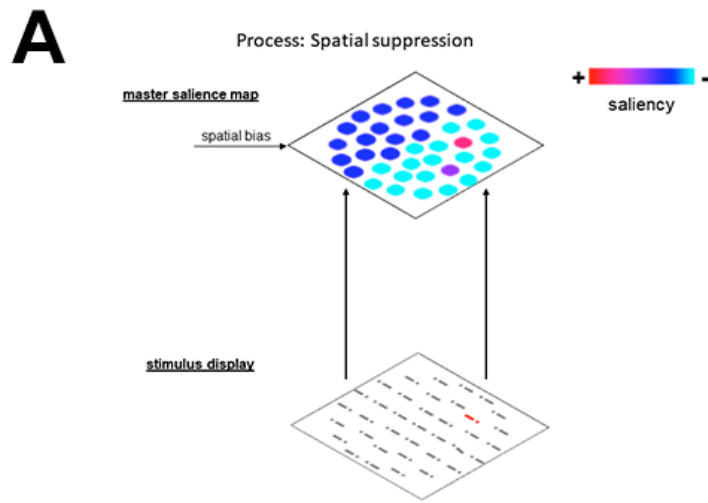


Figure 1. Schematic representations of three mechanisms conceivably involved in the probability cueing of distractor locations in visual search: (A) global-saliency suppression, (B) feature-based suppression, and (C) dimension-based suppression (illustrations for different-dimension distractors). The search displays depicted at the bottom of each sub-figure contains an orientation-defined target (12° tilted relative to vertical non-targets) and a color-defined distractor (red amongst gray items). The map depicted at the top of each figure is the search-guiding ‘master saliency map’. In all maps, hotter colors depict higher and cooler colors lower saliencies. (A) Distractor probability cueing could operate by spatially selective suppression of a larger area of the search display (in the example, the lower half) operating at the level master saliency map. (B) In the feature-weighting architecture, target and distractor features can be weighted independently of each other at the level of individual feature maps; accordingly, distractor signals can be down-weighted and target signals can be up-weighted independently of whether distractor and target are defined within the same or in different dimensions. (Note that non-target features take on only low values on their respective feature maps, due to the operation of ‘iso-feature’ suppression within each map). Distractor probability cueing could be explained by greater down-weighting of the distractor-defining feature in the frequent (lower half of the display) compared to the rare distractor region (upper half). (C) In the dimension-weighting architecture, the weighting of target and distractor signals occurs at the level of feature contrast signals combined for separable feature dimensions (i.e., dimension maps); i.e., feature weighting is dimensionally coupled, so that distractor signals cannot be down-weighted without affecting target signals when target and distractor are defined within the same dimensions. (Note that, in (C), the combined feature contrast signals from the color dimension are negatively weighted on their transfer to the master saliency map.) Distractor probability cueing could be explained by greater down-weighting of the distractor-defining dimension in the frequent (lower display half) compared to the rare distractor region (upper half). – With all architectures depicted, interference would be reduced for distractors appearing in the frequent as compared to the rare distractor region. In architecture (A), processing of targets appearing in the frequent distractor region would be affected in whatever dimension the target is defined. In architecture (B), target processing would not be affected, whether the distractor is defined within the same or a different dimension to the target. In architecture (C), target processing would be affected only if the distractor is defined within the same dimension as the target, but not when it is defined in a different dimension. Note that architectures (B) and (C) are compatible with each other, i.e., in principle, the weighting of specific features can be combined with the weighting of whole dimensions. See text for further explanations.

Based on the DWA, our working hypothesis was as follows: probability cueing (i.e., effectively stronger suppression applied to the frequent as compared to the rare distractor region) operates at the dimension-specific level when distractors are defined in a different dimension to the target – leaving target processing unaffected. But when distractors are defined within the same dimension as the target, space-based shielding operates (if it can operate at all) either at the dimension-specific level or at the level of the master map; both would be associated with a cost (i.e., a cost additive to any distractor-probability-cueing effect) for target processing in the frequent region as compared to the rare region.

We tested this hypothesis by comparing and contrasting the effects of same-dimension and different-dimension distractors. Distractor type was manipulated between

subjects (i.e., in separate experiments).³ Specifically, we examined (i) whether a distractor probability cueing effect would also be observed with same-dimension distractors (rather than only with different-dimension distractors); (ii) whether adaptation to the unequal distractor distribution (i.e., frequent vs. the rare distractor region) would also impact target processing; and (iii) whether any such impact would qualitatively differ between the same- and different-dimension distractor conditions.

In order to isolate pure distractor location probability cueing effects, the data need to be cleaned from short-term inter-trial repetition effects and effects of the distance between the target and the distractor in the search array, both of which can influence visual search and both of which may differ between the frequent and rare distractor regions. How we dealt with both types of potential confounds, and what impact they actually have on search performance is described in detail in the Appendix. Note that eliminating potentially confounding trials is costly in terms of the number of trials, or participants, required. We opted for recruiting a larger sample of participants – while keeping the number of trials manageable and consistent with Experiment 1 of Goschy et al. (2014) – by combining the data from several experiments with, in all important respects, identical design.

Method

Participants

One hundred and eighty-four (122 female, 62 male) right-handed observers, with a median age of 26 (range: 18–65) years, participated in the main experiment of this study.

³ The aim of the study was to examine focal hypotheses regarding the effects of target position (dependent on the type of distractor) in distractor probability cueing. These hypotheses were *not* examined by Goschy et al. (2014), who ignored the factor ‘target position’. We combined Goschy et al.’s (2014, Experiment 1) data with newly acquired sets of data to raise experimental power and support generalizability. The only difference in some of these new experiments was the non-target color, which was blue instead of gray. Of note, non-target color made no difference to the results, and even without the Goschy et al. (2014) data, the results are essentially the same.

They were recruited from participant panels at Ludwig Maximilian University Munich and Birkbeck College, University of London. All of them reported normal or corrected-to-normal (color) vision and gave prior informed consent. They received 8 € (or the GBP equivalent) per hour in compensation. Note that partial results based on the data of 25 of these participants were already reported in Goschy et al. (2014). One subject had to be removed from analyses for missing data (see Appendix).

Apparatus

The experiment was conducted in a sound-reduced, moderately lit test chamber. The search displays were presented on a CRT monitor at 1024 px × 768 px screen resolution and a refresh rate of 120 Hz. Stimuli were generated using either the Experiment Toolbox (Reutter & Zehetleitner, 2012), with a Psychophysics Toolbox 3.0.9 (Brainard, 1997; Kleiner et al, 2007) extension for MATLAB R2007a (The MathWorks® Inc) or OpenSesame 3.0 (Mathôt, Schreij, & Theeuwes, 2012) using a PsychoPy (Peirce, 2007) backend. The observers issued their responses using a QWERTZ [QUERTY] keyboard by pressing the “y” [“z”] or “m” key with their left- or right-hand index finger, respectively.

Stimuli

The stimulus displays were presented on a black background. They consisted of gray (RGB: 127, 127, 127; CIE [Yxy]: 21.22, 0.32, 0.32; for 112 participants) or light blue (RGB: 0, 140, 209; CIE [Yxy]: 57.3, 0.20, 0.20; for 72 participants) vertical non-target bars (0.25° of visual angle wide, 1.35° high), with their centers equidistantly arranged on three imaginary concentric circles with radii of 2° , 4° , and 6° , comprising of 6, 12, and 18 bars, respectively. A further bar occupied the position in the center of the three circles. In every bar, there was a gap of 0.25° in height, which was randomly located 0.25° from the top or bottom of the bar. The target differed from the non-targets by its unique orientation, randomly assigned on each trial: it was tilted 12° to either the right or the left. Note that 12° tilted targets (amongst

vertical nontargets) produce reliable ‘pop-out’, as evidenced by a flat search RT/set size function (with a slope near 0 ms/item) for such targets (Liesefeld, Moran, Usher, Müller & Zehetleitner, 2016), indicative of ‘efficient’ search.

If a singleton distractor was present, one of the non-targets was tilted 90° (horizontal; same-dimension distractor) instead of being vertical; or one of the non-targets was red (RGB: 255, 33, 51; CIE [Yxy]: 56.5, 0.60, 0.32) instead of gray (different-dimension distractor).

Note that the singleton target and (if presented) the singleton distractor could appear only at one of the 12 locations on the intermediate circle (i.e., singleton eccentricity was held constant). The non-target stimuli on the outer and inner circles (together with those on the intermediate circle) essentially served to equate local feature contrast amongst the various singleton positions (e.g., Bravo & Nakayama, 1992; Nothdurft, 1993).

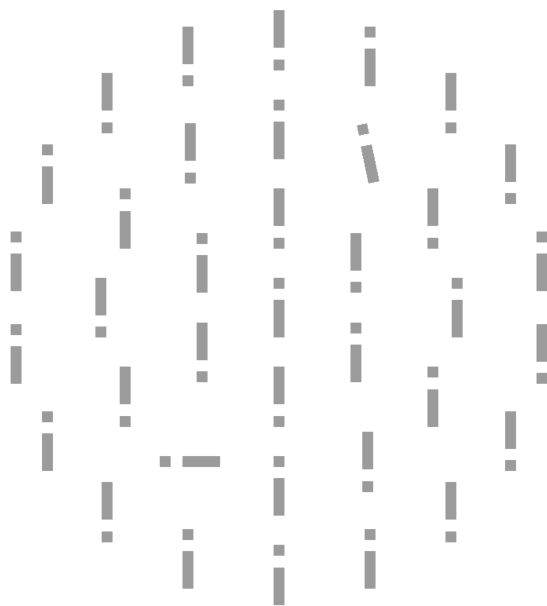


Figure 2. Example of a stimulus display. The search target is the 12°-tilted bar at the 1 o'clock position, and the (same-dimension) distractor is the 90°-tilted bar at the 7 o'clock position.

Design

The type of the singleton distractor (same- and different-dimension) was introduced as a between-subject factor, with 56 observers in the same-dimension condition and 128 in the different-dimension condition (including 25 from Goschy et al., 2014, Experiment 1). In addition to the type of distractor, the frequency distribution of the singleton distractor across the top and bottom halves of the search displays⁴ was manipulated as a between-subject factor, with the top half ranging from the 10 o'clock to the 2 o'clock positions and the bottom half from the 4 o'clock to the 8 o'clock positions on the intermediate circle (see Figure 2). For half of the participants, the top semicircle was the frequent distractor area (10 o'clock to the 2 o'clock positions); for the other half, the bottom semicircle was the frequent distractor area (4 o'clock to the 8 o'clock positions). Neither the distractor nor the target could appear at the 3 o'clock and 9 o'clock positions as these positions could not be unambiguously assigned to the frequent or rare area. A distractor was present in a random 50% of the displays per block. If a distractor was present, it appeared in the frequent area about 90% of the time ('frequent distractors') and in the rare area about 10% of the time ('rare distractors'). The target appeared equally often in both areas, with an equal probability for all 10 possible positions, but it never occurred at the same position as the distractor. The order of the trials within each block was randomized. The experiment consisted of 800 trials in total, subdivided into 8 blocks of 100 trials each.

Procedure

The experimental procedure was identical to that used by Goschy et al. (2014) in their Experiment 1. All observers were instructed in writing and orally that their task was to discern whether the target bar was interrupted (by a gap) at the top or the bottom. If it was

⁴ In Experiment 1 of Goschy et al. (2014), in addition to the top/bottom manipulation of distractor frequency as described here, there was also a left/right manipulation. Importantly, both 'polarity' manipulations produced comparable patterns of distractor interference effects, that is, there were no main or interaction effects involving the factor 'polarity'. Given this, only the top/bottom manipulation was used in further sampling for the present study.

interrupted at the bottom, participants had to press the “y” [“z”] key; if it was interrupted at the top, they had to press the “m” key. They were informed that on some trials, there would be a horizontal (same-dimension condition) or, respectively, a red (different-dimension condition) distractor bar which they should simply ignore, as it would be irrelevant to their task. Note that the distractor-defining feature was deliberately fixed, to permit observers to operate a feature-based suppression strategy (see ‘feature-weighting’ account above). Observers were not informed that the distractor would be more likely to appear in one particular semi-circle.

Each trial started with a white fixation cross in the middle of the screen presented for a random duration between 700 ms and 1100 ms. Then the search display appeared and stayed on until the observer gave a response indicating the gap position in the target bar. If the answer was incorrect, the word “Error” appeared in the center of the screen for 500 ms. Then the next trial started with the onset of the central fixation cross. After each block of trials, observers received RT and accuracy feedback and were free to take a short break before resuming the experiment.

After completing the experiment, participants filled in a brief questionnaire, which was intended to establish whether they had gained any explicit knowledge of the singleton distractors’ spatial frequency distribution (5 response alternatives, i.e.: were distractors equally likely in all display parts or were they more likely in the upper, lower, left, or right display half?).

Analysis

For the RT analyses presented below, we performed no (further) outlier rejection and computed median RT values per participant. We chose Cohen’s d to assess effect sizes. Apart from classical frequentist measures, to address issues raised by the ongoing ‘replication crisis’ (cf. Open Science Collaboration, 2015) acknowledged by 90% of scientists (Baker,

2016), we further report for our critical t tests (i) 95% highest-posterior-density intervals (HPD) computed with the “coda” package (Plummer et al., 2006) for R (R Core Team, 2014) as the credibility interval, which is a Bayesian parameter estimate (similar to confidence intervals), and (ii) standard JZS prior BF_{10} Bayes factors (Rouder et al., 2009) computed with the BayesFactor package (Morey & Rouder, 2015) for R. BF_{10} gives the relative evidence in the data in favor of H_1 , as compared to H_0 , that is, the likelihood to which H_1 predicts the observed data better than H_0 (see also Wagenmakers, 2007).

Results

In order to examine for pure statistical learning effects (here: learning of the distractor frequency distribution), potentially confounding effects arising from (i) certain inter-trial transitions as well as (ii) effects attributable to differential target-to-distractor distances between critical conditions, must be eliminated from the data set. Such effects were indeed observed and were subsequently eliminated. They exhibited interesting differential patterns between the same- and different-dimension distractor conditions. Although these effects are tangential to our main findings, we feel that they are of significant methodological importance and theoretical interest. Therefore, we report all analyses in detail in the *Supplementary Results* section and discuss the major findings in the General Discussion.

Analysis of distractor-interference effects

Our main prediction, deriving from the dimension-weighting account, was that the mechanisms underlying the distractor probability-cueing effect (evidenced by reduced interference by distractors in the frequent vs. the rare area) would give rise to impaired target processing only for targets defined within the same dimension as (but not targets defined in a different dimension to) the distractor and only for same-dimension targets located in the

frequent (but not targets in the rare) distractor region. To examine for this effect pattern, we first conducted an overall-ANOVA over the whole data set to establish interaction patterns. Based on these, we examined for the existence of the probability-cueing effect for both same- and different-dimension distractors, with a focus on differential target-(position-)related effects between the frequent and rare distractor areas. Finally, for a strong test of differential target-related effects, we directly examined for the predicted pattern on distractor-absent trials, specifically: would target processing be (differentially) impaired in the frequent distractor region even though there is no distractor in the display that could actually cause interference?

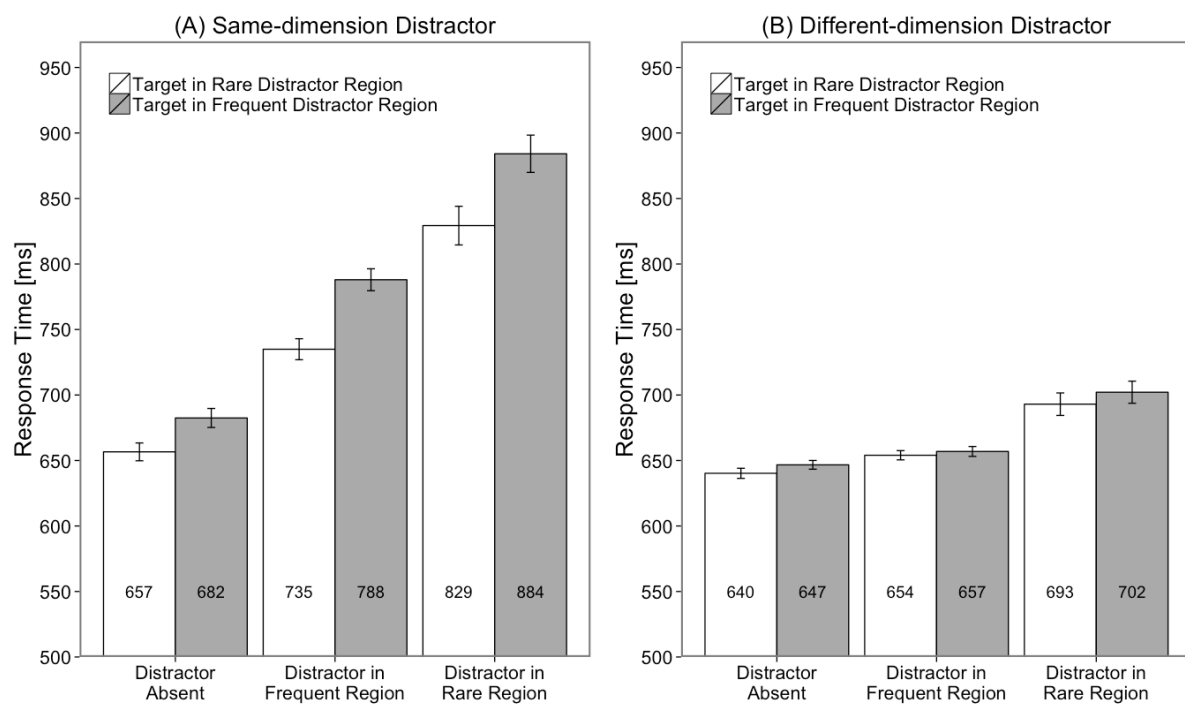


Figure 3. Mean RTs (calculated across participants' median RTs) for targets appearing in the frequent vs. rare distractor region as a function of the distractor condition (absent distractor, distractor in the frequent distractor region, distractor in the rare distractor region) in the same-dimension distractor (horizontal, orientation-defined distractor; panel A) and the different-dimension distractor condition (red, color-defined distractor; panel B). In both conditions, the distractor bar was presented among gray vertical bars and a slightly tilted gray target bar.

Error bars depict the within-subject SEM (Morey, 2008).

Participants' median correct RTs⁵ (for confound-free trials; see Appendix) were first subjected to an overall (mixed-design) ANOVA with main terms for distractor type (same- vs. different-dimension), distractor location (distractor in frequent area, in rare area, absent), and target location (target in frequent distractor area, in rare distractor area). This analysis revealed all main effects and two of the three two-way interactions – importantly, both involving the factor distractor type – to be significant⁶ (for visualization, see Figure 3). To elucidate the origins of the significant two-way interactions, the same- and different-dimension distractor conditions were examined in two separate (repeated-measures) ANOVAs with the factors distractor condition (distractor in frequent region, in rare region, absent) and target location (target in frequent distractor region, in rare distractor region).

Effects for same-dimension distractors. For same-dimension distractors, the ANOVA revealed both main effects to be significant: distractor location, $F(2,110) = 200.35$, $p < .001$, $\eta^2_p = .78$, and target location, $F(1,55) = 13.68$, $p < .001$, $\eta^2_p = .20$; the interaction was not significant, $F(2,110) = 1.74$, $p = .181$, $\eta^2_p = .03$.

To ascertain that distractors generally caused interference, we directly compared RTs on distractor-present trials with those on distractor-absent trials: RTs were overall slower, by 94 ms, when a distractor was present than when it was absent (761 ms vs. 667 ms; $t(55) = 14.94$, $p < .001$, $d_z = 2.00$, 95% HPD [81 ms, 106 ms], $BF_{10} = 8.80 \times 10^{17}$). To directly test for a probability-cueing effect, we contrasted the frequent versus rare distractor-present

⁵ Note that the error rates (overall error rate: 3.5%) were not influenced by distractor type (same-dimension vs. different-dimension), $F(1,181) = 1.50$, $p = .222$, $\eta^2_p = .01$, distractor location (frequent area, rare area, absent), $F(2,362) = 0.135$, $p = .874$, $\eta^2_p = .00$, or target location (frequent area, rare area), $F(1,181) = 0.175$, $p = .677$, $\eta^2_p = .00$. Also, none of the interactions was significant.

⁶ Main effects: distractor type, $F(1,181) = 30.34$, $p < .001$, $\eta^2_p = .14$; distractor location, $F(2,362) = 220.16$, $p < .001$, $\eta^2_p = .55$; and target location, $F(1,181) = 9.62$, $p = .002$, $\eta^2_p = .05$. Interactions: distractor type \times distractor location, $F(2,362) = 91.71$, $p < .001$, $\eta^2_p = .34$; and distractor type \times target location, $F(1,181) = 9.38$, $p = .003$, $\eta^2_p = .05$. The interactions distractor condition \times target location, $F(2,362) = 0.75$, $p = .471$, $\eta^2_p = .00$, and distractor type \times distractor location \times target location, $F(2,362) = 1.53$, $p = .219$, $\eta^2_p = .01$, were not significant.

conditions: RTs were indeed faster, by 87 ms, when a distractor was presented in the frequent area compared to the rare area (761 ms vs. 848 ms), $t(55) = -9.40$, $p < .001$, $d_z = 1.26$, 95% HPD [-116 ms, -73 ms], $BF_{10} = 3.27 \times 10^{10}$). Finally, we examined the net distractor-interference effect with reference to distractor-absent trials for the frequent and rare areas separately. Both effects were significant (distractors in rare area: 181 ms; $t(55) = 15.02$, $p < .001$, $d_z = 2.01$, 95% HPD [158 ms, 205 ms], $BF_{10} = 1.12 \times 10^{18}$; distractors in frequent area: 84 ms; $t(55) = 13.75$, $p < .001$, $d_z = 1.84$, 95% HPD [72 ms, 96 ms], $BF_{10} = 2.59 \times 10^{16}$), with distractors in the rare area causing greater interference than distractors in the frequent area.

Although the distractor condition \times target location interaction was not significant – indicative of an additive target-location effect for all three distractor conditions –, the target-location effect was numerically smaller when a distractor was absent in the display (25 ms) compared to when one was present in the frequent or the rare distractor region (53 and 55 ms, respectively). Despite being reduced, the effect on distractor-absent trials was significant: RTs were slower to targets appearing in the frequent versus the rare region (682 ms vs. 657 ms; $t(55) = 3.70$, $p < .001$, $d_z = .49$, 95% HPD [38 ms, 12 ms], $BF_{10} = 51$).

Thus, as expected (on the DWA), there was a significant effect of target location, with slower RTs when the target appeared in the frequent as compared to the rare distractor area. Importantly, this effect was evident even when distractors were absent, that is, when there could not be any distractor interference. This pattern provides strong support for the frequent distractor area being suppressed as a result of distractor (distribution) probability learning, affecting the processing of the target as well as that of the distractor.

Effects for different-dimension distractors. For different-dimension distractors, the ANOVA also revealed a significant main effect for distractor condition ($F(2,252) = 61.64$, $p < .001$, $\eta_p^2 = .33$), but (in contrast to same-dimension distractors) not for target location

($F(1,126) = 0.92, p = .339, \eta^2_p = .01$); the interaction was also not significant ($F(2,252) = 0.19, p < .827, \eta^2_p = .00$).

Distractors again caused general interference (main effect of distractor condition): RTs were slightly, but significantly, slower overall on distractor-present compared to distractor-absent trials (656 ms vs. 642 ms; $t(126) = 6.73, p < .001, d_z = 0.60$, 95% HPD [10 ms, 18 ms], $BF_{10} = 1.76 \times 10^7$); note that this interference effect was much smaller compared to that with same-dimension distractors (14 ms vs. 94 ms). Furthermore, a comparison of the frequent versus the rare distractor-present condition revealed RTs to be indeed faster when a distractor was presented in the frequent area compared to the rare area (654 ms vs. 689 ms), $t(126) = -6.10, p < .001, d_z = 0.54$, 95% HPD [-46 ms, -23 ms], $BF_{10} = 1.73 \times 10^6$), though this probability-cueing effect, too, was much smaller compared to that with same-dimension distractors (35 ms vs. 87 ms). Finally, as expected, the net distractor interference effect with reference to distractor-absent trials was greater for distractors in the rare area (47 ms; $t(126) = 7.74, p < .001, d_z = 0.69$, 95% HPD [34 ms, 59 ms], $BF_{10} = 2.79 \times 10^9$) than for distractors in the frequent area (11 ms; $t(127) = 5.93, p < .001, d_z = 0.53$, 95% HPD [7 ms, 15 ms], $BF_{10} = 4.05 \times 10^5$); these net effects of 47 ms (rare area) and 11 ms (frequent area) compare with 181 ms and, respectively, 84 ms for same-dimension distractors.

Concerning the (non-significant) target-location effect, RTs were overall only slightly slower to targets in the frequent versus targets in the rare distractor area. This effect was non-significant for all three distractor conditions (distractor absent: 647 vs. 640 ms; $t(126) = 1.43, p = .154, d_z = 0.13$, 95% HPD [15 ms, -2 ms], $BF_{10} = 0.27$; distractor in frequent area: 657 ms vs. 654 ms; $t(126) = 0.56, p = .580, d_z = 0.04$, 95% HPD [12 ms, -8 ms], $BF_{10} = 0.11$); distractor in rare area: 702 ms vs. 693 ms; $t(126) = -0.69, p = .493, d_z = 0.06$, 95% HPD [34 ms, -17 ms], $BF_{10} = 0.12$).

Distractor-absent trials. Arguably, the strongest evidence for learned, persistent spatial suppression on the master saliency map, or the lack of it, would derived from the distractor-absent trials, for which spatial suppression of target processing can be assessed in its pure form, without any effect of a competing distractor. Thus, to examine for differential suppression patterns between same- and different-dimension distractors, we directly compared and contrasted the effects of the two distractor types in the distractor-absent condition in a distractor type \times target location (mixed-design) ANOVA. This analysis revealed a significant main effect for target position ($F(1,181) = 10.71, p = .001, \eta^2_p = .06$), whereas the main effect of distractor type was non-significant ($F(1,181) = 3.11, p = .079, \eta^2_p = .01$). Importantly, the effect of target location was significantly modulated by the distractor type ($F(1,181) = 5.58, p = .019, \eta^2_p = .03$). Given this interaction, we compared the target-location effects (i.e., the mean differences between the two target-location conditions) between same- and different-dimension distractors. The results were in line with our hypothesis: the target-location effect (the disadvantage for targets appearing in the frequent vs. the rare area) was significantly larger with same-dimension (26 ms) than with different-dimension distractors (6 ms): $t(181) = 2.36, p = .019, d = 0.38, 95\% \text{ HPD } [8 \text{ ms}, 24 \text{ ms}], BF_{10} = 4.4$. Additionally, the target-location effect differed significantly from 0 for same-dimension distractors ($t(55) = 3.70, p < .001, d_z = .49, 95\% \text{ HPD } [11 \text{ ms}, 39 \text{ ms}], BF_{10} = 51$), but not for different-dimension distractors ($t(126) = 1.43, p = .154, d_z = 0.13, 95\% \text{ HPD } [-2 \text{ ms}, 15 \text{ ms}], BF_{10} = 0.27$).

Post-experiment questionnaires

We also examined whether the interference reduction for the frequent versus the rare distractor area depended on participants having ‘recognized’ the frequency distribution. If so, this would imply that the suppression of distractors in the frequent area might have relied on

a conscious effort. In the post-experimental questionnaire, 43 out of the 183 (23%) participants indicated the distractor frequency distribution correctly. While this would be chance level (recall that there were five response alternatives, so chance level would be 20%), it should be noted, however, that the majority of participants (53%) opted for the response ‘equal distribution’, rather than committing to a specific region in which distractors were (believed to be) likely.⁷ When committing to a specific response, the correct distractor region was significantly more likely to be chosen than any of the three alternatives (55% vs. 45% [= 3 × 15%]; $\chi^2(1) = 30.73, p < .001$) – indicative of a degree of awareness of the actual distractor distribution. Importantly, the degree of ‘awareness’ was little influenced by the distractor type: 20% and 25% correct answers (given 5 response alternatives, including the ‘equal-distribution’ option) with same- and different-dimension distractors, respectively. Of those who committed to a specific response, 48% (same-dimension distractors, $\chi^2(1) = 4.15, p = .042$) and 57% (different-dimension distractors; $\chi^2(1) = 23.76, p < .001$) answered correctly.

Comparing participants who answered correctly with those who responded incorrectly (including those who gave an ‘equal-distribution’ answer) in an awareness (correct/incorrect answer) × distractor type (same-/different-dimension) × distractor location (frequent/rare area) ANOVA of the median RTs revealed no two-way interactions involving awareness (awareness × distractor type, $F(1, 179) = 1.75, p = .188, \eta^2_p = .01$; awareness × distractor location, $F(1, 179) = 3.21, p = .075, \eta^2_p = .02$), but the three-way interaction was significant, $F(1, 179) = 7.56, p = .007, \eta^2_p = .04$. Follow-up ANOVAs, with the factors awareness and distractor location, calculated separately for each distractor-type condition, failed to reveal significant main effects of awareness for both different-dimension and same-dimension distractors (different-dimension distractors, $F(1, 125) = 0.03, p = .858, \eta^2_p = .00$; same-

⁷ Note that the response alternative ‘equal distribution’ was introduced to exactly follow the awareness-test procedure of Goschy et al. (2014).

dimension distractors, $F(1, 54) = 2.65, p = .110, \eta^2_p = .05$). However, for same-dimension distractors (but not different-dimension distractors, $F(1, 125) = 0.01, p = .915, \eta^2_p = .00$), the awareness \times distractor location interaction was significant: $F(1, 54) = 9.49, p = .003, \eta^2_p = .15$, reflecting the fact that (the 11) ‘aware’ participants showed a larger probability-cueing effect than (the 45) ‘non-aware’ participants (158 ms vs 83 ms; $t(54) = 3.08, p = .003, d_z = 1.04$, 95% HPD [91 ms, 141 ms], $BF_{10} = 12$). Given that the overall RT speed was comparable between the ‘aware’ and ‘non-aware’ groups (774 ms vs 745 ms; $t(54) = 0.77, p = .443, d_z = 0.26$, 95% HPD [720 ms, 793 ms], $BF_{10} = 0.408$), the larger probability-cueing effect for the ‘aware’ participants provides an indication that, with same-dimension (but not with different-dimension) distractors, the probability-cueing effect may be (strategically) enhanced as a result of observers explicitly recognizing the display half in which the distractor was more or, respectively, less likely to appear.

Discussion

The present study revealed a paramount difference in the probability-cueing effect between same- (orientation-) and different- (color-) dimension distractors in visual singleton search. While both distractor-type groups showed significant learning of the spatial distractor distribution (as evidenced by reduced interference from distractors that appeared in the frequent, as compared to the rare, distractor area), the interference was higher overall – by a factor of at least 4 – with same- relative to different-dimension distractors. In addition, there was a qualitative difference in the interference pattern caused by same- versus different-dimension distractors. Search under conditions of same-dimension distractors was associated with a target-location effect (i.e., slowed responding to targets appearing in the frequent vs. the rare distractor region). This was observed even for displays that did not contain a distractor. No target-location effect was evident in search under conditions of different-

dimension distractors. We will discuss the implications of these effects in turn, while also touching upon the issue of the nature – implicit versus explicit – of distractor probability learning.

Same-dimension distractors cause greater interference than different-dimension distractors

The differential magnitude of interference between same- and different dimension distractors is in line with previous reports that distractors that are similar to the search target cause more interference to begin with (e.g., *DWA*: Müller et al., 2009; Zehetleitner et al., 2012; *ambiguity account*: Olivers & Meeter, 2006; Meeter & Olivers, 2006; Pashler, 1987)⁸. Additionally, the present data show that shielding from the interference generated by distractors frequently occurring in a particular display area *cannot* be learned as effectively with target-similar as with target-dissimilar distractors: same-dimension distractors continued to produce strong interference even in the frequent distractor area, which compares with weak interference by frequent-area distractors in the different-dimension condition.

This effect pattern argues against feature-based accounts, according to which distractor suppression is achieved by the independent down-weighting of distractor features (first-order order feature suppression) and/or up-weighting of target features. In theory (cf. Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992; Wolfe & Horowitz, 2017), independent weighting of target and distractor features should work effectively as long as the features are clearly separable. In the present study, this was the case not only in the different-dimension condition, but also in the same-dimension condition: the distractor was consistently rotated

⁸ While this pattern can be described in *similarity* (or *ambiguity*) terms, we propose it reflects fundamental, dimension-based constraints in the functional architecture of search guidance. Further research is necessary to discriminate between the essentially continuous similarity (or ambiguity) vs. discrete dimension-based accounts.

by 90° from the vertical as compared to a variable (left or right) target tilt of 12°. According to Wolfe et al. (1992), this is a ‘categorical’ feature difference capable of guiding search. Apparently, however, this categorical difference could not be exploited by participants in the same-dimension distractor condition, effectively ruling out a strict, feature-based account (at least for the orientation dimension).

Instead, a straightforward, mechanistic account of the differential interference between same- and different-dimension distractors effects is provided by the DWA: due to the (assumed) hierarchical organization of saliency computation and dimensionally coupled weighting of feature-contrast signals (e.g., Zehetleitner et al., 2012), it is harder to suppress known distractors defined by features in the same dimension as the target, compared to features in a different dimension. As will be detailed below, DWA readily explains why distractor interference is greatly increased overall in the same-, as compared to the different-, dimension condition (94 vs. 14 ms). Interference effects approaching 100 ms suggest that attention was actually captured by the distractor on a large majority of trials (consistent with Liesefeld, Liesefeld, et al., 2017, who also used orientation-defined distractors and targets).

Differential mechanisms underlie the probability-cueing effects in same- versus different-dimension distractors

The differential pattern of distractor location probability-cueing effects – specifically, the differential target location effects between the same- and different-dimension conditions – cannot be explained by spatially selective versions of either feature-based (or first-order feature) suppression models or global-saliency suppression models. Global-saliency suppression would predict *impaired* processing of targets in the frequent distractor region, regardless of whether the distractor is defined in the same or a different dimension to the target. Feature-based suppression models would always predict *unimpaired* processing of

targets in the frequent distractor region, regardless of whether distractors are defined in the same or a different dimension to the target. The fact that target processing in the frequent region was slowed only in the same-, but not in the different-, dimension distractor condition effectively rules out that either of these mechanisms can account for the present set of findings on its own.

But this pattern is consistent with the DWA, according to which the distractor-defining dimension can be suppressed as a whole, with greater suppression applied to the frequent than to the rare distractor area. However, dimension-based (or second-order feature) suppression would leave target processing unaffected only when the distractor is defined in a different dimension to the target. By contrast, when the distractor is defined in the same dimension as the target, two strategies of reducing distractor interference would be available: dimension-based suppression or global-salience suppression, in both cases with stronger suppression assigned to the frequent than to the rare distractor region – that, however, would both impair target processing. With both strategies, the power of distractors appearing in the frequent area to capture attention would be reduced, compared to distractors in the rare area, giving rise to probability-cueing effects. But the downside would be that targets falling in the frequent (i.e., suppressed) region are responded to *slower* than targets in the rare region. Both these effects were evidenced by the data, consistent with either of the two strategies.

With same-dimension distractors, dimension-based suppression would appear to be a less plausible strategy than global-salience suppression, as any down-weighting of the orientation dimension would conflict with the task of finding the orientation-defined target.⁹

However, no such conflict would arise if the down-modulation is applied to the (spatial)

⁹ To solve the task, observers would have to actively maintain a template of the orientation target in visual working memory, to decide whether a stimulus that summons attention is a target (rather than a distractor), as well as to top-down bias search towards stimuli matching the target description (e.g., Soto, Hodsoll, Rotshtein, & Humphreys, 2008; Olivers, Peters, Houtkamp, & Roelfsema, 2011). There would thus be a goal conflict with observers, at the same time, attempting to keep any signals from the orientation dimension out of the search and selectively enhancing the target orientation.

master saliency map. This representation is assumed to be feature- and dimension-less. Master map activations as such convey no information as to how, by which feature and in which dimension, they were produced. Rather, post-selective back-tracking to lower, dimension- and feature-coding, levels may be required to extract this information (e.g., Töllner, Rangelov, & Müller, 2012). Given this, applying spatial inhibition at this level would conflict less with the goal of finding and responding to an orientation-defined target. Additionally, the target-location effect was even evident on distractor-absent trials, strongly supporting spatially selective global-saliency suppression at the master map level.

With different-dimension distractors, distractor interference can be rather effectively reduced by dimension-based suppression – as a result of which feature-contrast signals from this dimension arrive attenuated at the saliency summation stage (the master map), reducing their power to capture attention. Importantly, to explain the probability-cueing effect (35 ms faster RTs to targets in the frequent vs. the rare area), one would have to additionally assume that, as a result of probability learning, the dimension-based down-modulation of feature-contrast signals from the distractor dimension becomes stronger for the frequent than for the rare distractor area. Stronger down-modulation of feature contrast signals from the distractor dimension within the frequent area would leave target signals from another dimension unaffected. Consistent with this, RTs were *not* significantly slower to targets in the frequent area than to targets in the rare area.

Of note, this qualitative difference between the two distractor-type conditions is even seen in a comparison of the *distractor-absent* trials, on which cannot be any ‘confounding’ by a competing additional singleton in the display: here, there was no reliable target location effect with different-dimension distractors, but a significant (26-ms) effect with same-dimension distractors – despite generally similar RT levels on distractor-absent trials (on which the displays were identical for the two groups).

Implications for the cognitive architecture underlying distractor probability cueing

These results have implications for drawing conclusions about the cognitive architecture mediating the distractor probability (distribution) learning effects: Suppression of *different-dimension* distractors operates at a level below the master saliency map. Interfering feature-contrast signals from the distractor-defining dimension are down-modulated, so that their contribution to overall-saliency signaling is effectively reduced, yielding lower distractor interference overall; at the same time, feature-contrast signals from the target dimension are left unaffected. By contrast, same-dimension distractors generate a comparatively large interference effect, and RTs are significantly slowed when the target appears in the frequent as compared to the rare distractor area – even when no distractor (that could cause interference) is actually present in the display. The latter effect is readily explained by assuming that the frequent distractor region is suppressed either at the super-ordinate level of the master saliency map (our preferred account), or, alternatively, at the level of the orientation-dimension map, which in both cases would affect target as well as distractor signals.

However, while the present findings are ‘in line’ with the DWA (the only general account predicting a dissociation between same- and different-dimension distract!), further work – for instance, with luminance-, color-, and motion-defined targets (and distractors defined in either the same or one of the other dimensions) – is necessary for the DWA to be established as a truly general account of the asymmetry revealed in the present study. Of note, there is evidence that, within the color dimension, salient singletons mismatching the target color (i.e., same-dimension distractors) may fail to capture attention (e.g., from contingent-capture studies, with temporally separated presentation of the singleton distractor and target displays: Folk, Leber, & Egeth, 2002; Lien, Ruthruff, & Cornett, 2010; Lien,

Ruthruff, & Johnston, 2010; and from additional-singleton studies, with target and distractor in the same display: e.g., Gaspar & McDonald, 2014; Gaspar, Christie, Prime, Jolicoeur, & McDonald, 2016). Note, though, that, although non-matching colors interfered relatively little (compared with matching colors), the interference was significant (with the exception of Folk et al., 2002, Experiment 2, who used an attentional-blink paradigm with accuracy as dependent measure).¹⁰ Based on this evidence, it would appear that the suppression of color distractors does involve an element of feature-based suppression (see also Gaspelin, Leonard, & Luck, 2015, and Gaspelin & Luck, 2017, for evidence of first-order, as opposed to second-order, color feature suppression in a paradigm with shape targets and color distractors, where the distractor color was either constant/predictable [Gaspelin et al., 2015] or variable/non-predictable [Gaspelin & Luck, 2017] across trials). This picture is actually consistent with previous studies of dimension weighting (with combinations of color, motion, and orientation targets), in which color proved to be special: it was the only dimension producing significant feature-specific inter-trial priming and trial-wise pre-cueing effects¹¹ (e.g., Found & Müller,

¹⁰ For instance, in Gaspar & McDonald (2014, Experiment 1: yellow target, red distractor, presented amongst green non-targets), the color distractor generated significant interference of 18 ms; while it produced no N2pc (which would have been indicative of attentional capture), it elicited a P_D (i.e., with a midline target, the ERP waveform was more positive contralateral vs. ipsilateral to the distractor 250–300 ms post display onset), which is thought to reflect – in this case: feature-based – distractor suppression (e.g., Hickey, Di Lollo, & McDonald, 2009; Sawaki, Geng, & Luck, 2012). Note though that a significant P_D was evident only on fast-response trials, but not on slow-response trials, suggesting failure of distractor suppression on some proportion of (slow-response) trials.

¹¹ For instance, Found & Müller (1996) found that, in color/orientation pop-out search, repetition of the precise target color feature across trials (e.g., red → red) conferred an advantage over a color switch (e.g., blue → red), with the latter yielding an advantage compared to a dimension switch (e.g., right-tilted → red). With orientation-defined targets, by contrast, only a dimension-specific switch effect was seen. Similarly, Müller et al. (2003) found that when a particular target color was precued to be likely at the start of a trial (e.g., red, cue validity $p=.79\%$), there was a significant advantage for targets singled out by this feature compared to targets defined by another color feature (e.g., blue, $p=.07$) or by an orientation feature (45° left- or right-tilt, each $p=.07$). Of note, there was also some advantage for targets defined by the non-cued color feature (i.e., blue when the cue indicated red; same-dimension feature) compared to the two orientation features (different-dimension features) even though all non-cued features were equally unlikely. For orientation-defined targets, by contrast, there was no significant feature-specific cueing effect, i.e., no graded advantage for the cued vs. the non-cued orientation feature. These results point to a greater role of feature-specific coding for the color dimension compared to the orientation dimension.

1996; Müller et al., 2003; Weidner, Pollmann, Müller, & von Cramon, 2002) – underscoring the dictum that ‘not all features or dimensions were created alike’ (e.g., Nothdurft, 1993; Wolfe, Chun, & Friedman-Hill, 1995). Accordingly, feature-based distractor suppression may be possible, to some extent, with color distractors (which produce relatively small intra-dimensional interference effects; e.g., Gaspar & McDonald, 2014; Gaspar et al., 2016), while it does not appear to be possible with orientation distractors (which produce large intra-dimensional interference effects; e.g., Liesefeld, Liesefeld, et al., 2017, and present study). Nevertheless, given the available evidence from dimension-weighting studies, we would predict dimension-based effects to outweigh feature-based effects even with color distractors. Purpose-designed studies, with carefully calibrated color and orientation stimuli, as well as generalization to other combinations of singleton (target and distractor) dimensions involving luminance, color, and motion stimuli, would be necessary to examine this prediction. This is beyond the scope of the present study.

Assuming reasonable generalizability, note that the search architecture envisaged by DWA does not exclude feature-based selection – which is, after all, assumed to be the prime principle of non-spatial selection in virtually all models of visual search and selective attention (*Guided Search*, e.g., Wolfe, 2007; *template-based guidance*, e.g., Duncan & Humphreys, 1992). DWA only claims that for features defined within the same dimension, one cannot independently modulate one feature-contrast signal (e.g., the target signal) from another (e.g., the distractor signal) as regards their cross-dimensional *integration/summation weights* by units of the master saliency map. While some theorists have criticized DWA for being unable to account for findings of feature selectivity, one straightforward extension would be to assume a combination of independent intra- and cross-dimensional weights: intra-dimensional weights would ensure that one can, to some extent, up-modulate the target feature and/or down-modulate the distractor feature in the computation of dimension-specific

(i.e., within-dimensions) feature contrast signals (as assumed by, e.g., Guided Search).

However, both these (feature-weighted) signals would then be multiplied by the same dimensional weight on being transferred to the master saliency map. Such a scheme would ensure an element of feature selectivity, while also maintaining the principle of dimensional weight coupling – which is at the heart of DWA!

Distractor probability cueing: explicit or implicit in nature?

In previous studies of distractor location probability cueing (Goschy et al., 2014; Leber et al., 2016), participants were typically unable, at the end of a lengthy experiment, to tell at above-chance level at which locations distractors were likely to appear. This was taken to suggest that the distractor probability cueing effect is essentially implicit in nature (Reder et al., 2003, too, assume that their *negative location priming* effect operates outside conscious awareness, though without having examined for this). However, all these studies employed only relatively small numbers of observers (e.g., 19 participants in Goschy et al., 2014; 26 participants in Leber et al., 2016), making it hard to actually establish above-chance recognition of the likely distractor locations. Given our large sample, we had reasonable power to determine whether participants could tell above chance in which display region a distractor was most likely to appear. While responses appeared to be at chance when looking at the proportion of participants who correctly selected the frequent distractor region (out of the total number of observers), a more detailed analysis revealed significant above-chance performance among those participants who did not choose a non-committal, ‘equal-distribution’ response. This was the case whether participants had performed the task under the different- or the same-dimension distractor condition. As same-dimension distractors caused massive interference, one could have surmised that a majority of observers might

have become aware of the unequal distribution – which was, however, not borne out by the data.

Partitioning the participants into two ‘awareness’ groups (‘aware’ = correct answer, ‘unaware’ = incorrect answer) and re-examining the probability-cueing effect as a function of group revealed no significant main effect of ‘awareness’. However, there was an interaction of ‘awareness’ with distractor condition for the same-dimension group, with ‘aware’ participants exhibiting a larger probability-cueing effect (157 ms, which compares with 83 ms, that is, half the effect, for the ‘non-aware’ group), without responding significantly slower. This would argue that (perhaps the majority of) these 11 observers became genuinely aware of the distractor frequency distribution, which made them increase the inhibition they applied to the frequent distractor area. Of note this would predict that aware participants also exhibit an enlarged target position effect – which is, at least numerically, borne out by the data. Note, however, that above chance performance does not necessarily imply awareness, and further studies are necessary to resolve this question (ideally excluding the ‘equal-distribution’ response and including confidence ratings).

Thus, our data provide some indication (at variance with Goschy et al., 2014, who had only a small sample of participants compared to that analyzed in the present study and who examined only correct versus all incorrect, including ‘equal-distribution’, responses) that distractor probability cueing might reflect, at least to some extent, an explicit learning effect. This would place distractor probability cueing with other, perceptual-learning effects in the search literature, notably *contextual cueing* – an effect that is similarly associated with a (limited) degree of explicit awareness of repeatedly encountered target-nontarget configurations (Smyth & Shanks, 2008, and Vadillo, Konstantinidis & Shanks, 2015; though see Chun & Jiang, 2003; Colagiuri & Livesey, 2016; Goujon & Thorpe, 2015). Note, though, that whether conscious awareness drives distractor probability cueing is another matter:

conceivably, the effect may be implicitly driven, while being associated with (a degree of) explicit awareness (see Geyer, Müller, Assumpcao, & Gais, 2013, with regard to contextual cueing). However, with same-dimension distractors – which require enhanced cognitive control to deal with capture events – observers who became consciously aware of the distractor distribution appeared to adjust the strength of spatial suppression accordingly. No such adaptation was evident with different-dimension distractors, presumably because these require a lesser degree of cognitive control to be filtered out effectively.

Location-specific inter-trial and lateral-inhibition effects

The supplementary analyses (see Appendix for details) revealed significant modulations of RTs by positional inter-trial effects, in particular, expedited RTs when the current (trial n) target appeared at the location of the previous (trial $n-1$) target ($T_{n-1}-T_n$ transition) – in line with the *positional*-priming literature in visual search (e.g., Maljkovic & Nakayama, 1996; Kumada & Humphreys, 2002; Geyer, Müller, & Krummenacher, 2007). This is interesting because we used relatively dense displays (with 36 items), whereas hitherto positional inter-trial effects have been investigated and reported mainly with relatively sparse displays (as with the *priming of pop-out* paradigm, where displays typically consist only of three relatively widely spaced items). On the other hand, positional inter-trial priming effects have been reported by Krummenacher et al. (2009) for both singleton detection and compound-search tasks (both with dense displays): RTs were expedited to targets on trial n that appeared at (roughly) the same position as the target on trial $n-1$, and this effect was more marked for compound-search than for simple detection tasks, even though the target singleton was exactly the same in both cases. Related to distractor probability cueing, Goschy et al. (2014) had found evidence that, to some extent, the interference reduction for the frequent (as compared to the rare) distractor area was due to

positional inter-trial effects, in particular: interference was reduced when the distractor on the current trial occurred at the same location as the previous distractor ($D_{n-1}-T_n$ transition) – a finding confirmed in the present study. Additionally, the present, more comprehensive inter-trial analysis showed that if a target appears at the same location as the last distractor ($D_{n-1}-T_n$ transition) or if a distractor occurs at the same location as the last target ($T_{n-1}-D_n$ transition), RTs are slowed. Given that such repetition effects were much more likely to happen in the frequent as compared to the rare distractor area, they would have affected both areas differentially and thereby confounded the results. This highlights the necessity to control for positional inter-trial effects when examining effects of distractor location probability cueing.

Theoretically of potential importance, the inter-trial transition effects – that is, both the (inter-trial) distractor-location inhibition ($D_{n-1}-T_n$ trials: 53 ms vs. 13 ms; $D_{n-1}-D_n$ trials: -32 ms vs. -2 ms), and to some extent also the target-location facilitation (at least on $T_{n-1}-T_n$ trials: -70 ms vs. -49 ms) – were greatly increased in the same-, relative to the different-dimension, condition (distractor-location inhibition was increased by a factor of at least 4!).

In addition to positional inter-trial effects, the supplementary analyses revealed significant intra-trial modulations of RTs by the spatial distance of the target relative to the distractor. It is thought that when a salient distractor captures attention, it must be (actively) suppressed for focal attention to move on to the next most salient item, the target (see, e.g., Liesefeld, Liesefeld, et al., 2017), and this suppression affects not only the distractor location itself, but spreads laterally to the surrounding region, tailing off gradually with increasing distance from the distractor location (e.g., Gaspar & McDonald, 2014; Mathot, Hickey, & Theeuwes, 2010; Mounts, 2000).¹²

¹² Attentional capture by the distractor may not actually be necessary for target-to-distractor distance effects to manifest. For instance, Gaspar and McDonald (2014) observed a behavioral distance effect (of maximally 55 ms) even though, in their event-related analysis of the EEG, they found no N2pc to the distractor.

Importantly, in the present study, this intra-trial lateral inhibition effect centered on the distractor position was also greatly increased, by a factor of three, for same-dimension compared to different-dimension distractors (measured in terms of the rate of RT decrease as a function of the distance of the target from the distractor: -12.99 ms vs. -4.72 ms per degree of visual angle). This pattern mirrors the increased cross-trial distractor location inhibition with same- as compared to different-dimension distractors, suggesting that it is the inhibition brought to bear on the distractor on a given (distractor-present) trial that is then carried over into the next trial.

Overall, this pattern is consistent with the idea that the harder the search and, particularly, the harder it is to shield from distractor interference, the greater the positional intra- and inter-trial effect. Concerning the intra-trial inhibition (and the cross-trial carry-over of inhibition) of the distractor location, the more likely it is that the distractor captures attention, the greater the suppression applied. There may be two explanations for this: One is that, on a given trial, the amount of inhibition placed on the distractor location is increased in the different-, compared to the same-, dimension distractor condition. Alternatively, the amount of inhibition is the same on a single-trial basis, but given that same-dimension distractors generate capture more frequently (i.e., on a greater number of trials), these also have to be actively suppressed more frequently (on a greater number of trials), giving rise to an, on average (i.e., across trials), increased inhibition effect in this condition. The idea is that a distractor that captured attention (once it is established by a post-selective analysis process that it is a distractor, rather than a target) must be actively inhibited (see Liesefeld, Liesefeld, et al., 2017, for ERP evidence for this sequence of events), so that it does no longer compete for selection. The amount of inhibition may either be adjusted to the difficulty of keeping the distractor out of the search, or it may be a fixed amount per capture incident regardless of this difficulty. Future work is required to distinguish between these possibilities.

Conclusions

While same-dimension distractors cause four times greater interference than different-dimension distractors, the probability-cueing effect (i.e., reduced interference by distractors in the frequent vs. the rare region) is evident with both types of distractors. However, the effect is much stronger for same-dimension distractors, which also display a robust target-location effect (slower responses to targets appearing in the frequent versus the rare distractor region). The latter is indicative of a strong component of general, spatial suppression of the frequent distractor region, which we propose, operates at the level of the master saliency map, on top of any feature-based modulations. With different-dimension distractors, by contrast, there was a probability-cueing effect but no target-location effect. While the probability-cueing effect is also attributable to an element of differential spatial suppression between the frequent and rare distractor regions, this operates at a level prior to the search-guiding master saliency map, selectively down-modulating feature-contrast signals from the distractor dimension so that they register only weakly on the master saliency map. The improved ability to suppress distractors in the frequent region appears to be acquired implicitly, without observers being consciously aware of the unequal distractor distribution; though, with very salient distractors, at least some observers may become aware of the unequal distractor distribution and deliberately increase the amount of frequent-region suppression. Given this, open questions for future work concern whether explicit information about the distribution can modulate the effect, whether the current explanatory framework generalizes to other dimensions, and whether possible alternative explanations can be dissociated via direct tracking of attention allocations and suppression mechanisms by means of event-related potentials.

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Appendix

Supplementary Introduction

When examining for distractor probability cueing, it is important to make sure that there is an effect of statistical learning of spatial cues over and above that of mere inter-trial repetitions. For instance, it is known that in, singleton-search episodes, distractor locations are inhibited or negatively tagged, increasing the time it takes for a feature contrast signal at such a location to reach the level of salience required to summon attention (Cepeda, Cave, Bichot & Kim, 1998; Kumada, 1999; see also Dent, Allen, Braithwaite & Humphreys, 2012). Thus, given that inhibitory tagging of previous distractor locations is, by definition, more likely in the region where distractors occur frequently, a (subsequent) distractor falling in this region would be more likely affected compared to a distractor in the rare distractor region – mimicking a learnt probability-cueing effect and thereby reducing distractor interference, when, in fact, the effect is driven purely by (passive) inter-trial dynamics. Goschy et al. (2014) attempted to control for this type of inter-trial effect in a dedicated experiment (their Experiment 3) in which the distractor on trial n (D_n) could, by design, not fall on the location of the distractor on trial $n-1$ (D_{n-1} ; inter-trial transition $D_{n-1}-D_n$). Goschy et al. indeed found that the differential interference between the frequent and rare distractor areas was reduced as a result of ruling out $D_{n-1}-D_n$ transitions, but there remained a robust effect attributable to the learning of probability cues. However, changing the design of the experiment (as Goschy et al., 2014, did to exclude distractor-location repetitions) may have led to a change in participants' search strategy and thus to a change in the effect sizes. For this reason, we opted for another approach to eliminate inter-trial effects: in the present study, we allowed all possible cross-trial (location) transitions to occur, but partialled out the inter-trial effects by excluding potentially affected trials post-hoc from analysis. A further advantage conferred by this procedure is that it permitted us to quantify the inter-trial effects (i.e., the extent to which

they account for the ‘probability-cueing’ effect) within the same experiments (participants) (i.e. without changing the experimental design).

A second caveat concerns examination for the predicted target-position effect (in the same-dimension condition). It is thought that when a salient distractor captures attention, it must be (actively) suppressed for focal attention to move on to the next most salient item, the target (see, e.g., Liesefeld, Liesefeld, et al., 2017), and this suppression affects not only the distractor location itself, but spreads laterally to the surrounding region, tailing off gradually with increasing distance from the distractor location (e.g., Gaspar & McDonald, 2014; Mathot, Hickey, & Theeuwes, 2010; Mounts, 2000). Now (with the display arrangement realized in Goschy et al., 2014, and the present study; see Figure 2), with a distractor in the frequent area, a target in the frequent area would, on average, be nearer to the distractor than a target in the rare area (in the present design as well as that of Goschy et al., 2014, the target-distractor separation around the circle on which the two singletons were arranged varied between 1 unit [target and distractor adjacent] and 4 units [target and distractor separated by three intervening stimuli on the circle] when target and distractor were located in the same area, but between 2 and 6 units when they were located in different areas). That is, a target in the same area as the distractor would be more likely affected by lateral inhibition than a target in a different area to the distractor, giving rise to slower reaction times to targets in the frequent as compared to the rare region. Critically, an additional target position effect in the same direction is also predicted by our DWA-based hypothesis for the same-dimension distractor condition.¹³ Thus, to remove any confound with this effect in terms of lateral

¹³ Note, however, that, on the DWA, the additional spatial effect should occur exclusively for same-dimension, but not different-dimension, distractors; and it should occur even for distractor-absent trials, on which there is no distractor in the display that would need to be inhibited for focal attention to be allocated to the target. The lateral-inhibition effect, by contrast, would occur equally with same- and with different-dimension distractors, but only on distractor-present, not on distractor-absent, trials. Furthermore, with a distractor in the rare area, a target in the rare area would, on average, be nearer to the distractor than a target in the frequent area and thus be more affected by lateral

inhibition, analysis must be restricted to (only) such trials for which the target-distractor distance is equated between conditions with a distractor located in the frequent area and those with a distractor in the rare area. In the present study, this was done by restricting analyses to separations of 3 units (9.85° of visual angle) and 4 units (12.07°) only (there were too few trials with a separation of 2 units).

Supplementary Results

As elaborated above, in order to examine for pure statistical learning effects (here: learning of the distractor frequency distribution), potentially confounding effects – specifically, effects arising from (i) certain inter-trial transition effects as well as (ii) effects attributable to differential target-to-distractor distances between critical conditions – were eliminated from the data set. Such effects exhibited interesting differential patterns between the same- and different-dimension distractor conditions, as detailed in the following two sections.

Inter-trial effects. A major confound is likely given by (current) trials on which the distractor, D_n , appears at the location of the last distractor, D_{n-1} . In such D_{n-1} – D_n transitions, the current distractor falls on a location that is inhibitorily tagged (as a result of the distractor on the previous trials falling on this position) and is therefore less potent in attracting attention and causing interference. As such transitions are more likely for the frequent than for the rare distractor area, they would enhance any differential interference effects between the frequent and the rare distractor region that might arise from statistical learning. As indicated by Goschy et al. (2014; comparison of their Experiment 2 with Experiment 1), a significant part of the differential interference effects between distractors in the frequent versus the rare area is indeed attributable to such D_{n-1} – D_n transitions. However, there are

inhibition. While this would again predict a target position effect (RTs to rare-area targets being slower than RTs to frequent-area targets), the effect is actually in the opposite direction to that predicted by the DWA-based account. On the latter, RTs to frequent-area targets should be generally slower than RTs to rare-area targets, even on distractor-absent trials and no matter whether the distractor is located in the frequent or the rare region on target-present trials.

other inter-trial transitions (besides D_{n-1} – D_n transitions – the only ones controlled for by Goschy et al., 2014, in their Experiment 3) that may affect the magnitude of distractor interference, notably, (i) a (current) target falling at the same position as the previous distractor (D_{n-1} – T_n) and (ii) a (current) distractor falling at the same position as the previous target (T_{n-1} – D_n). Concerning case (i), given carry-over of inhibitory tagging, a (current) target falling at the same position as the previous distractor would make the current target less potent (i.e., it would take longer to achieve salience and attract focal attention). As instances of type D_{n-1} – T_n would be much more likely for the frequent distractor area, this could also skew the results regarding statistical learning of distractor frequency distributions, though in the opposite direction to D_{n-1} – D_n transitions: D_{n-1} – T_n transitions would reduce the differential distractor interference between the frequent and the rare area. Concerning case (ii), there is evidence of positive tagging (and carry-over) of the target location on a given trial (e.g., Krumenacher et al, 2009). Accordingly, a (current) distractor falling on the previous target location (T_{n-1} – D_n) would be more potent, that is, achieve salience faster and thus be more competitive for attracting focal attention. As such instances, too, are more likely for the frequent distractor area, they would again skew the results: again in the opposite direction to D_{n-1} – D_n transitions.¹⁴

All these effects were evident in the present data set. For instance, on distractor-present trials (i.e., on which the current distractor had the potential to produce interference), RTs (to the target) were slower when the target appeared at the same location as the last distractor (D_{n-1} – T_n) as compared to a different location (728 ms vs. 704 ms; $t(183) = 6.72$, $p < .001$, $d_z = 0.50$, 95% HPD [17 ms, 33 ms], $BF_{10} = 3.5 \times 10^7$), and when a distractor appeared at the same location as the last target (T_{n-1} – D_n) as compared to a different location (716 ms

¹⁴ Note that target location repetitions across successive trials (T_{n-1} – T_n) were balanced between the frequent and rare distractor areas; accordingly, such repetitions should not impact any differential distractor interference effects between the frequent and rare regions.

vs. 704 ms; $t(183) = 3.92, p < .001, d_z = 0.29$, 95% HPD [6 ms, 17 ms], $BF_{10} = 116$). Finally, RTs (to the target) were faster when the distractor appeared at the same location as the last distractor ($D_{n-1}-D_n$), as compared to a different location (693 ms vs. 704 ms; $t(183) = -4.34, p < .001, d_z = .32$, 95% HPD [-15 ms, -5 ms], $BF_{10} = 575$).

Interestingly, these inter-trial effects differed between the two distractor types. An ANOVA with the factors inter-trial transition type (no location repetition, $D_{n-1}-T_n$, $D_{n-1}-D_n$, $T_{n-1}-D_n$, $T_{n-1}-T_n$) and distractor type (same-dimension vs. different-dimension) revealed, besides main effects of distractor type, $F(1,182) = 44.52, p < .001, \eta_p^2 = .20$, and inter-trial transition, $F(4,728) = 110.47, p < .001, \eta_p^2 = .38$, the interaction to be significant, $F(4,728) = 18.01, p < .001, \eta_p^2 = .09$. In follow-up t tests, the RTs of the four inter-trial repetition conditions were contrasted with the ‘no-repetition’ baseline separately for different and same-dimension distractors. For *different-dimension* distractors, compared to the baseline (668 ms), RTs were slightly slowed, by a little over 10 ms, to targets appearing at a previous distractor location ($D_{n-1}-T_n$: 681 ms; $t(127) = 3.50, p < .001, d_z = .31$, 95% HPD [6 ms, 20 ms], $BF_{10} = 31$), or when the current distractor appeared at a previous target location ($T_{n-1}-D_n$: 680 ms; $t(127) = 4.14, p < .001, d_z = 0.37$, 95% HPD [7 ms, 19 ms], $BF_{10} = 263$). There was little facilitation (-2 ms) when the current distractor appeared at the previous distractor location ($D_{n-1}-D_n$: 666 ms; $t(127) = -0.46, p = .644, d_z = .04$, 95% HPD [-6 ms, 5 ms], $BF_{10} = 0.11$), but substantial facilitation (-49 ms) when the current target appeared at the previous target location (619 ms; $t(127) = -11.08, p < .001, d_z = .98$, 95% HPD [-57 ms, -40 ms], $BF_{10} = 2.21 \times 10^9$). For *same-dimension* distractors, compared to the baseline (789 ms), RTs were substantially slowed, by over 50 ms, when the current target appeared at the previous distractor location ($D_{n-1}-T_n$: 842 ms; $t(55) = 6.85, p < .001, d_z = .91$, 95% HPD [37 ms, 69 ms], $BF = 1795702$), while there was relatively little slowing (9 ms) when the current distractor appeared at the previous target location ($T_{n-1}-D_n$: 798 ms; $t(55) = 1.35, p = .182, d_z$

= 0.18, 95% HPD [-5 ms, 22 ms], $BF_{10} = 0.34$). There was sizeable facilitation (-32 ms) when the current distractor appeared at the previous distractor location ($D_{n-1}-D_n$: 757 ms; $t(55) = -6.69$, $p < .001$, $d_z = 0.89$, 95% HPD [-40 ms, -21 ms], $BF_{10} = 1019639$), and even greater facilitation (-70 ms) when the current target appeared at the previous target location ($T_{n-1}-T_n$: 719 ms; $t(55) = -8.08$, $p < .001$, $d_z = 1.08$, 95% HPD [-85 ms, -50 ms], $BF_{10} = 1.54 \times 10^8$). Thus, the interaction effect derives from the fact that especially the (inter-trial) distractor-location inhibition ($D_{n-1}-T_n$ trials: 53 ms vs. 13 ms; $D_{n-1}-D_n$ trials: -32 ms vs. -2 ms), and to some extent also the target-location facilitation (at least on $T_{n-1}-T_n$ trials: -49 ms vs. -70 ms), was greatly increased in the same-, relative to the different-, dimension condition (distractor-location inhibition was increased by a factor of at least 4!).

As already said, location transitions involving the distractor happened more often in the frequent distractor area (therefore confounding the results). On average across participants, a target appeared at the same location as the previous distractor absolutely more often in the frequent ($N = 30$) compared to the rare distractor region ($N = 4$); a distractor appeared at the same location as the previous distractor much more often in the frequent ($N = 59$) than in the rare distractor region ($N = 1$); also, a distractor appeared in the same location as the previous target absolutely (and relatively somewhat) more often in the frequent distractor region ($N = 39$) than in the rare distractor region ($N = 4$). Given their distribution imbalances, all these inter-trial transitions should be – and, in the present study, were – excluded for the analysis of ‘pure’ statistical learning effects.¹⁵

Target-to-distractor distance effects. Another confound in the present study may be that targets are subject to differential amounts of lateral inhibition (arising from the

¹⁵ Note that, in the present study, the results remained similar after removal, which is because the two effects of distractor-distractor transitions ($D_{n-1}-D_n$) facilitating processing and distractor-target transitions ($D_{n-1}-T_n$) impairing processing (in the frequent area) largely cancel each other out. Also note that target-target ($T_{n-1}-T_n$) transitions do not affect the probability-cueing effect, as such transitions are equally likely in both (the frequent and the rare) distractor areas.

suppression of distractors that captured attention) depending on whether they are located within the same area as the distractor (i.e., both in the frequent or the rare distractor area, in which case the average distance of the target to the distractor would be smaller and therefore the inhibitory influence larger) or in different areas (in which case the average distance would be larger and therefore the inhibitory influence smaller). Such lateral-inhibition effects could conceivably add to (distractor in frequent area) or take away from (distractor in rare area) the target-position effect predicted on the DWA-based account – though only under distractor-present conditions!

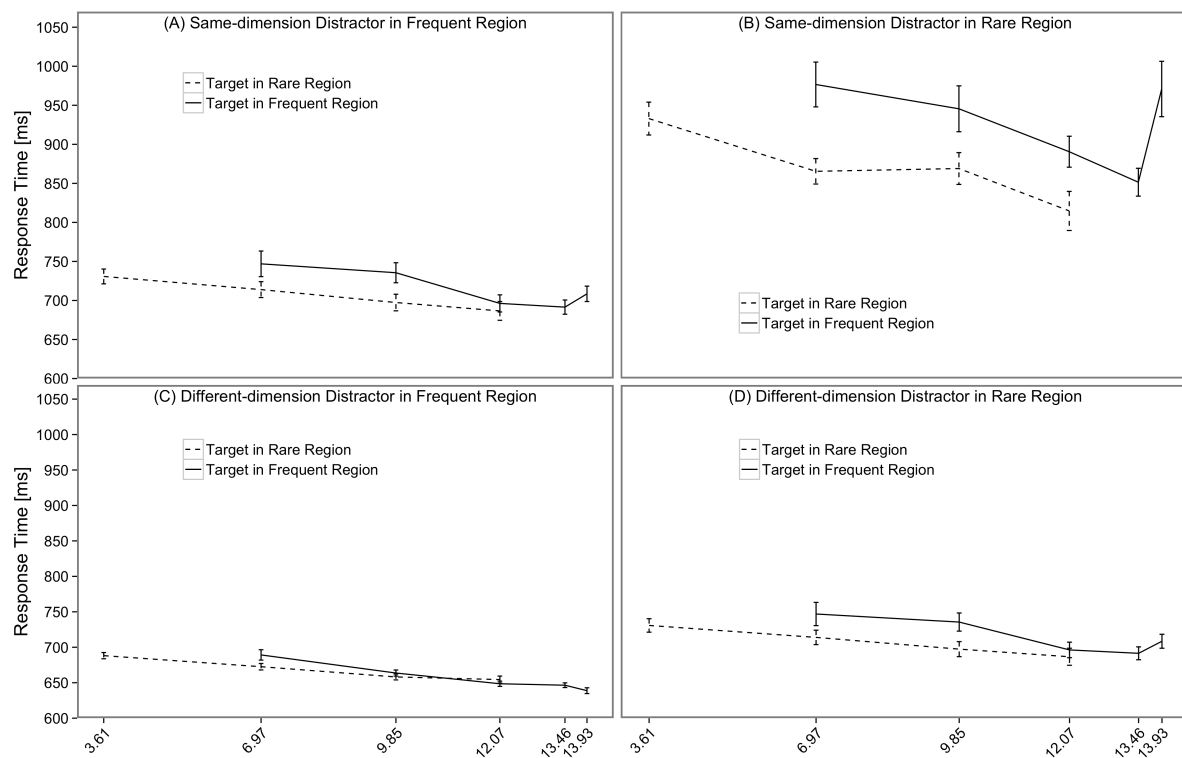


Figure A1. Mean RTs as a function of target-to-distractor distance (in degrees of visual angle), for each of the combinations of distractor location (distractor located in frequent vs. rare region: left- vs. right-hand panels) \times target location (target located in frequent vs. rare distractor region), separately for the two distractor types (same- vs. different-dimension: upper vs. lower panels).

For the present data, the lateral-inhibition effects are depicted in Figure A1. Each panel presents RT as a function of the distance (in degrees of visual angle) of the target from the distractor, separately for targets located in the frequent and targets located in the rare distractor area; these functions are shown separately for same- and different-dimension distractors (upper and lower panels) appearing in the frequent and rare distractor areas (left and right panels), respectively. As can be seen from the (fairly linear) decreases in RTs with increasing target-distractor separation, lateral-inhibition effects do manifest in all conditions.¹⁶ Furthermore, the amount of lateral inhibition, measured in terms of the rate of RT decrease per unit of distance (i.e., degrees of visual angle), appears overall more marked for same- than for different-dimension distractors ($-12.99 \text{ ms}/^\circ$ vs $-4.72 \text{ ms}/^\circ$; $t(72.73) = -6.1$, $p < .001$, $d_z = 1.18$, 95% HPD $[-9.897 \text{ ms}/^\circ, -7.582 \text{ ms}/^\circ]$, $\text{BF}_{10} = 1.193\text{e}+09$ ¹⁷).

To make sure we compare like with like in the critical analyses of distractor-interference effects, we went on to examine RTs as a function of distractor location (distractor-in-frequent- vs. distractor-in-rare-area) \times target–distractor distance (9.85° vs. 12.07°) \times target position (same vs. opposite area with respect to distractor). The latter variable was included as, conceivably, the gradient of the inhibition applied might differ between the two distractor areas – in which case lateral inhibition would vary even for equivalent distances. Distractor location \times distance \times target position (repeated-measures) ANOVAs performed separately for same- and different-dimension distractors failed to reveal any interactions between target position and distance (target position \times distance: $F(1,47) = 0.71$ and, respectively, $F(1,89) = 0.02$, $ps > .1$; distractor location \times target position \times distance:

¹⁶ This pattern is consistent across the range of distances for conditions with a distractor in the frequent area, for which we have relatively reliable estimates. The one deviant value for the greatest separation with a same-dimension distractor in the rare area and a target in the frequent area is likely attributable to a measurement error, given the few trials available for this extreme, distractor-in-rare-area condition.

¹⁷ Slopes calculated excluding the most extreme distance of 13.93° .

$F(1,47) = 0.04$ and, respectively, $F(1,89) = 1.22, p = .272$).¹⁸ That is, there was no evidence of a modulation of any target-position effects by distractor-to-target distance (the main effect of target position was significant for the same-dimension, but not for the different-dimension condition: $F(1,47) = 11.29, p = .002$, vs. $F(1,89) = 0.30, p = .585$). Restated, for equivalent distractor-to-target distances (and for a given type of distractor appearing in a given area), target-position effects, if any, are simply additive to the lateral-inhibition effects. Thus, by including in the analysis of target-position effects only ‘equated’ distances, we can be confident that any effects on target processing revealed are not confounded by differential amounts of lateral inhibition when the target is located within the same versus the opposite area to the distractor.

Accordingly, prior to analysis of the distractor interference effects reported below, we dealt with (potential) *inter-trial transition confounds* by eliminating all trials on which (i) the current distractor appeared at the exact same position as the previous distractor ($D_{n-1}-D_n$); (ii) the current target appeared at the exact same position as the previous distractor ($D_{n-1}-T_n$); and (iii) the current distractor appears at the exact same position as the previous target ($T_{n-1}-D_n$) – which resulted in the removal of 17% of the trials. Furthermore, to deal with *lateral-inhibition confounds*, we only included (distractor-to-target) distances in the analysis that were common to the conditions with targets in the frequent and targets in the rare distractor area – specifically, distances of 9.85° , and 12.07° , for all distractor-type \times distractor-position combinations. The latter two distances were included because missing values were minimal at these distances (only one participant had to be excluded) and the distances could be effectively equated between the target-in-frequent- and target-in-rare-distractor-area

¹⁸ Due to missing values, the number of observers that could be entered into these analyses was reduced from 56 to 48 in the same-dimension distractor condition and from 128 to 90 in the different-dimension condition.

conditions. Including only these two, equated distances in the distractor-interference analysis led to the omission of a further 26% of the trials.